Diagnostic accuracy of a smartphone electrocardiograph in dogs: Comparison with standard 6-lead electrocardiography

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Abstract: The diagnostic accuracy of a smartphone electrocardiograph (ECG) in evaluating heart rhythm and ECG measurements was evaluated in 166 dogs. A standard 6-lead ECG was acquired for 1 min in each dog. A smartphone ECG tracing was simultaneously recorded using a single-lead bipolar ECG recorder. All ECGs were reviewed by one blinded operator, who judged if tracings were acceptable for interpretation and assigned an electrocardiographic diagnosis. Agreement between smartphone and standard ECG in the interpretation of tracings was evaluated. Sensitivity and specificity for the detection of arrhythmia were calculated for the smartphone ECG. Smartphone ECG tracings were interpretable in 162/166 (97.6%) tracings. A perfect agreement between the smartphone and standard ECG was found in detecting bradycardia, tachycardia, ectopic beats and atrioventricular blocks. A very good agreement was found in detecting sinus rhythm versus non-sinus rhythm (100% sensitivity and 97.9% specificity). The smartphone ECG provided tracings that were adequate for analysis in most dogs, with an accurate assessment of heart rate, rhythm and common arrhythmias. The smartphone ECG represents an additional tool in the diagnosis of arrhythmias in dogs, but is not a substitute for a 6-lead ECG. Arrhythmias identified by the smartphone ECG should be followed up with a standard ECG before making clinical decisions.

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RELIABILITY OF A SMARTPHONE ELECTROCARDIOGRAM DEVICE IN DOGS: COMPARISON WITH STANDARD 6-LEAD ELECTROCARDIOGRAPHY

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Abbreviations: HR, heart rate; App HR, heart rate automatically measured by the smartphone application; AVB, atrioventricular block; QTc, corrected QT interval.

ABSTRACT

Objective–To assess the reliability of a smartphone electrocardiogram (ECG) device in evaluating heart rhythm and ECG measurements in dogs.

Design–Prospective, multicenter, single-blind study.

Animals–166 client-owned dogs.

Procedures–A standard 6-lead ECG was acquired for 1 minute in each dog. A smartphone ECG tracing was simultaneously recorded using a single-lead bipolar ECG recorder. All ECGs were reviewed by one blinded operator, who judged if tracings were acceptable for interpretation and assigned an electrocardiographic diagnosis. Agreement between smartphone and standard ECG in the interpretation of tracings was evaluated. Sensitivity and specificity for the detection of arrhythmia were calculated with the smartphone ECG.

Results–Smartphone ECG tracings were interpretable in 162 out of 166 (97.6%) tracings. A perfect agreement between the smartphone and standard ECG was found in detecting bradycardia, tachycardia, ectopic beats and atrioventricular blocks. A very good agreement was found in detecting arrhythmias, with a 100% sensitivity and 97.9% specificity.

Conclusions and clinical relevance–The smartphone ECG provides tracings that are adequate for analysis in most dogs with a reliable assessment of heart rate, heart rhythm, atrioventricular blocks or ectopic beats. Remote smartphone ECG assessment can support the use of standard ECG in the management of dogs with arrhythmias.

Introduction

Many arrhythmias have paroxysmal presentation, while others require frequent monitoring due to the risk of progression. In these settings, serial electrocardiograms (ECG) are crucial for correct diagnosis and management. Clinical electrocardiography has thus undergone a continuous technological evolution since its invention by Willem Einthoven in 1903, leading to the development of Holter monitoring, telemetry systems and loop recorders.[1]

One of the latest innovations is the 1-lead ECG recorded by smartphone devices using specific applications.[2-4] Most smartphone ECG devices automatically digitize the electrocardiographic tracings. Some instruments enable PDF tracings to be uploaded to a cloud storage service or to send PDF files via email for remote interpretation. In human medicine there are many studies highlighting the good accuracy of smartphone ECG tracings to measure the heart rate (HR) and evaluate heart rhythm.[5-7]

Other studies have shown the good performances of smartphone ECG devices for QT interval assessment in patients receiving antiarrhythmic therapy,[8,9] for diagnosing supraventricular tachycardia in pediatrics,[10-12] for detecting atrial fibrillation[5,13-17] and for identifying signs associated with myocardial ischemia.[18,19] Despite the considerable number of articles published in human medicine regarding the feasibility, accuracy and usefulness of smartphone ECG devices, to the best of our knowledge only one preliminary study has been performed comparing a smartphone ECG device to standardized ECG tracings in dogs.[a] The aim of the present study was therefore to assess the use and reliability of a smartphone ECG to evaluate heart rhythm and ECG measurements in dogs.

Materials and methods

Animals

The study group included client-owned dogs that were referred to the Department of Veterinary Science of the University of Pisa or the Department of Cardiology of the Istituto Veterinario di Novara for a cardiologic consultation or assessment prior to anesthesia. The study was prospective, multicenter and single-blind. Dogs were recruited over a one-year period, from December 2014 to December 2015. Each case underwent a cardiac evaluation, including physical examination, standard 6-lead ECG and echocardiogram. The study protocol was reviewed and approved by the Institutional Welfare and Ethics Committee of the University of Pisa (permission number 39/2015). Written consent authorizing the participation of dogs in the study was obtained from each owner.

ECG acquisition and analysis

A standard 6-lead ECG[b,c] was acquired for 1 minute in conscious, unsedated dogs that were positioned in right lateral recumbency. A smartphone ECG tracing was simultaneously recorded by three operators (TV, CB, FM) with an iPhone 4S[d] using a single-lead bipolar ECG recorder[e] and its application.[f] The smartphone ECG was recorded placing it on the left precordial area of all the dogs. A cranio-caudal orientation of the smartphone case was used in each dog (Figure 1). In the short-haired dogs, a small amount of alcohol was placed on the left precordial area in order to obtain a good quality smartphone ECG signal. In the long-haired dogs, a small amount of alcohol was placed after shaving the left precordial area in order to acquire the same high-quality signal. The standard ECGs were stored digitally. Smartphone ECG recordings were automatically digitized by the device, sent via email and stored as a PDF. For each dog, ECG tracings obtained with the two methods were printed at a paper speed of 50 mm/s with a gain of 10 mm/mV. If QRS complexes had a very high or very low amplitude, a 5 mm/mV or a 20 mm/mV gain was used, respectively. The last 30 s of each ECG tracing were analyzed. Dogs with a smartphone ECG trace lasting < 30 s were excluded from the study.

All ECG tracings were reviewed by a board-certified veterinary cardiologist (OD), in a blinded fashion, who judged whether the tracings were acceptable for interpretation. For all ECG tracings, the same operator evaluated the rhythm and performed ECG measurements. Measurements were achieved using the lead II of the standard ECG and using the only available lead of the smartphone ECG.

In each case, the following measurements were performed: mean HR (beats per minute, bpm); P wave amplitude (mv) and duration (ms); PQ interval duration (ms); R wave amplitude (mV); QRS complex duration (ms); QRS polarity; ST segment elevation or depression (mV); QT interval duration (ms); and corrected QT interval (QTc). The latter was calculated using the following formula: $QTc = \log 600 \times QT/\log RR$.[20] The mean HR was calculated by counting the number of QRS complexes in the last 30 s of the print out of each tracing. The result was multiplied by two in order to obtain the number of bpm. The QRS polarity of the smartphone ECG traces was compared with lead II of the standard ECG. Other measurements were achieved as previously described.[21] Amplitude and duration measurements were calculated as the mean of three different beats. Finally, the mean HR calculated automatically by the smartphone application (App HR) was noted. Heart rate was classified as normal if between 70 and 160 bpm, bradycardia if < 70 bpm and tachycardia if > 160 bpm, as previously described.[21]

Statistical analysis

The analysis was performed only with paired ECG tracings that were considered acceptable for interpretation, as defined by the operator, and the standard ECG was set as the reference method. Cohen's kappa (κ) test was used to calculate the agreement between the smartphone ECG and standard ECG for HR classification (normal, bradycardia or tachycardia), heart rhythm (sinus rhythm, atrial fibrillation, ventricular rhythm, supraventricular rhythm), atrioventricular blocks (AVB) (absent, first-degree AVB, second-degree AVB, third-degree AVB), premature complexes (absent, ventricular, supraventricular), ST segment (normal, elevated or depressed), polarity of QRS complex (positive, negative) and QTc interval (normal, long or short). The kappa coefficient was interpreted as follows: values ≤ 0.20 as no agreement, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as good, 0.81–0.99 as very good, and 1 as perfect agreement.

The sensitivity, specificity, positive and negative predictive values of the smartphone ECG to detect arrhythmia were calculated. In addition, the median and range of differences between the standard ECG and smartphone ECG were calculated for the amplitude of the P and R waves, for the duration of the P wave, PQ interval, QRS complex and QTc interval. The Pearson or Spearman correlation coefficients were used to study correlations between HRs measured with the standard ECG and the smartphone ECG using values calculated either by the operator or automatically . The Shapiro-Wilk test was used to determine the normality of the datasets. Statistical analysis was performed with a commercial software.[g] $P < 0.05$ was considered as significant.

Results

Animals and feasibility

A total of 166 dogs were enrolled in the study, of which 84 were males and 82 were females. The median age was 9 years (ranging between 0.3 to 17 years) and median body weight was 25 kg (55.1 lb) with a range of 2.1 to 75 kg (4.6 to 165.3 lb). The majority of dogs (71 out of 166, 43%) had cardiac diseases, both congenital or acquired; 32 dogs (19%) had neoplastic diseases, 31 (18%) were in the intensive care unit because of renal, respiratory, gastro-intestinal or neurologic diseases, and 33 (20%) were healthy dogs evaluated for pre-anesthesia assessment prior to elective surgeries.

The blinded operator judged 162 of 166 (97.6%) of the smartphone ECG tracings as acceptable for interpretation (Figures 2, 3 and 4). In 4 cases (2.4%), the tracings were deemed as non-interpretable; all of tracings were recorded in dogs with a body weight < 10 kg.

Heart rate

According to the standard 6-lead ECG, 133 out of 162 dogs (82%) had a normal HR, 20 (12%) had tachycardia, and 9 (6%) had bradycardia. A perfect agreement (κ=1) between the smartphone and standard ECG was found in the classification of HR when it was manually measured on digitized tracings (Table 1). A strong positive correlation was found between the HR values obtained by both methods ($r^2 = 0.99$; $p < 0.0001$; Figure 5). Median paired differences between the HR manually measured on standard ECG and smartphone ECG was 0 bpm (-10, +20 bpm; Table 2 and Figure 6). A strong positive correlation was also found between the App HR values and those manually measured on standard ECG tracings ($r^2 = 0.923$; $p < 0.0001$; Figure 7). However, the App HR was less accurate than the manually measured HR on digitized smartphone ECG tracings (κ=0.91). In fact, in 103 out of 162 (63.6%) cases, the App HR underestimated the actual HR, with a median difference of -3 bpm; (-31, +20 bpm; Figure 8). However in only 4/162 (2.5%) cases, was there a misclassification of HR with the smartphone application. According to App HR, two dogs with tachycardia were classified as normal HR, one dog with normal HR was classified as bradycardia, and one dog with bradycardia was classified as normal HR. The greatest disagreement was found in a dog with severe bradycardia (40 bpm) secondary to a third-degree AVB in which the App HR read the P waves as QRS complexes, thus erroneously yielding an HR of 140 bpm.

Heart rhythm

One hundred and forty-one dogs (87%) had sinus rhythm or sinus arrhythmia; 14 dogs (9%) had supraventricular arrhythmias; 7 dogs (4%) had ventricular rhythm or ventricular arrhythmias. Six dogs (4%) had different types of AVBs.

Very good agreement (κ=0.94) was found in the evaluation of the heart rhythm. Disagreement was found in only 3 out of 162 (1.9%) cases, in which the sinus rhythm was erroneously classified as atrial rhythm due to the negative polarity of the P waves (1 case) or as a slow atrial fibrillation due to non observable P waves (2 cases) on the smartphone ECG trace (Table 3). In 128 out of 149 (85.9%) cases, the smartphone ECG underestimated the amplitude of the P wave, with a median difference of -0.1 mV (-0.4; +0.1 mV). The analysis of the P wave duration showed a median difference between the two methods of 0 ms (-20, +0 ms).

QRS complex analysis

A good agreement (κ=0.65) was found in the polarity of the QRS complexes between the smartphone ECG and lead II of the standard 6-lead ECG (Figures 2, 3, 4). The same QRS polarity was found in 158 out of 162 (97.5%) cases. In 3 cases with positive polarity of the QRS complex in lead II, the smartphone tracing showed a negative QRS. In 1 case with negative polarity of the QRS complex in lead II, the smartphone tracing showed a positive QRS. The evaluation of the QRS duration showed a median difference of 0 ms (-20, +10 mV). Lastly, the smartphone ECG underestimated the amplitude of R wave in 121 out of 162 (74.7%), with a median difference of -0.5 mV (-2.1; +1), compared to the standard ECG.

Ectopic beats

A perfect agreement (κ=1) between the smartphone ECG and standard ECG was found in the identification and classification of ectopic beats, including 16 cases with ventricular premature complexes, 3 cases with supraventricular premature complexes and 4 cases with both supraventricular and ventricular ectopic beats. In addition a perfect agreement was found regarding the polarity of ventricular premature complexes on the smartphone ECG tracings compared with lead II of the standard 6-lead ECG.

Atrioventricular blocks

A perfect agreement (κ=1) between the smartphone ECG and standard ECG was found in the AVB diagnosis, including 2 cases with first-degree AVB, 1 with second-degree AVB and 3 cases with third-degree AVB. The PQ interval analysis using smartphone tracings was reliable in comparison to the standard ECG, with a median difference of 0 ms (range -20, +20 ms).

QT interval and ST segment

In the interpretation of the ST segment and QT interval, the agreement between the smartphone ECG and standard ECG was good (κ=0.70 and κ=0.72, respectively). In 2 dogs with a normal ST segment on the standard ECG, the smartphone ECG erroneously indicated ST depression in 1 case and ST elevation in the other. In 2 dogs the smartphone ECG did not identify the ST depression, which was evident on the standard ECG. In our study, the smartphone ECG underestimated the QT interval, with a median difference of -10 ms (range -34, +19 ms) compared to the standard ECG. Five cases of long QT intervals were erroneously classified as normal QT intervals using tracings recorded with the smartphone ECG.

However, in 7 cases with moderately to severely increased QT intervals (QTc >260 ms), the long QT was correctly identified.

Performance with arrhythmias

Considering all the arrhythmias taken together, the smartphone ECG had 100% sensitivity and 97.9% specificity in differentiating between sinus rhythm and arrhythmias, with a positive predictive value of 87.5%, and a negative predictive value of 100%.

Discussion

In our investigation the smartphone ECG was easily performed in all dogs and 96.7% of tracings were deemed as interpretable. These results are in line with findings in human medicine where smartphone ECG tracings were interpretable in 87-99% of patients.[12,13,22] The few tracings judged as non-interpretable were all recorded in small breed dogs, where motion artifacts are common, which likely accounted for the fact that the tracings were not readable.

The smartphone ECG was excellent in the HR evaluation in dogs, since a strong positive correlation was found between the HR values obtained by the smartphone device and the standard ECG. This is in accordance with a preliminary study in dogs, where instantaneous and average heart rates were identical in all cases where exact matches were possible in a comparison between smartphone ECG and reference ECG.[a]

In our investigation, the greatest reliability was found when the HR was manually measured on digitized tracings. Conversely the App HR was less reliable, since lower agreement was found between the HR values obtained by the smartphone device and the standard ECG.

As the QRS complexes on smartphone ECG tracings had a low amplitude in most dogs, we hypothesize that the App HR may underestimate the HR due to the fact that some QRS complexes are not correctly interpreted by the instrument. In a few dogs, the App HR was totally unreliable. However, in only 1 case the disagreement was of a real clinical value: in a dog with severe bradycardia secondary to third-degree AVB, the App HR read the P waves as QRS complexes, thus erroneously resulting in a normal HR.

The smartphone ECG was very reliable in evaluating heart rhythm in dogs, as it showed 100% sensitivity and 98% specificity in the detection of arrhythmias. The recorded arrhythmias were also accurately identified using the smartphone ECG, in most instances. All cases of atrial fibrillation were correctly diagnosed, without false negatives. This result is similar to findings in humans where the sensitivity and specificity of the smartphone ECG in detecting atrial fibrillation were 94-100% and 90-97%, respectively.[5,7,22] In humans, most false diagnoses of atrial fibrillation are due to small voltage P waves. Our results showed that the smartphone ECG underestimates the amplitude of the P wave. Despite this, the P waves remained clearly visible in the majority of dogs with sinus rhythm. In a few cases, however, the P waves were difficult to recognize and occasionally it was hard to differentiate between sinus rhythm and atrial fibrillation. Consequently, 2 out of 141 cases of sinus rhythm were incorrectly classified as atrial fibrillation. In a small breed dog, the P waves had negative polarity on the smartphone ECG leading to the incorrect diagnosis of an atrial ectopic rhythm. A preliminary study in cats recommended positioning the smartphone case parallel to the long axis of the heart, with a more base-apex orientation in comparison to our cranio-caudal orientation.[h] It might be that in some small breed dogs, the orientation of the smartphone case should be individually adjusted to correctly visualize the P waves. Atrial fibrillation is common in dogs with severe cardiac disease and increases the risk of cardiac-related death in those with myxomatous mitral valve degeneration and dilated cardiomyopathy.[23,24] Likewise, in humans, atrial fibrillation increases the chance of morbidity or mortality, and recent studies have highlighted the utility of the smartphone ECG in screening for this arrhythmia.[5,7,13-

[16,25,26] A significant number of occult atrial fibrillations have been detected by physicians, pharmacists or directly by patients using an ECG recorded with a smartphone.

Early diagnosis of atrial fibrillation is difficult in dogs. Our results show that the smartphone ECG may become a promising tool for frequent monitoring of dogs predisposed to atrial fibrillation. It could also be beneficial for dogs with atrial fibrillation that receive drugs to control HR. Holter monitoring is an essential tool for evaluating HR and in treating atrial fibrillation in dogs. However, 24-hour Holter monitoring is expensive and necessitates the owner's compliance, hence its use may not always be practical. In the light of its ease and cost effectiveness, the smartphone ECG could represent a complementary tool for HR evaluation at home in dogs with atrial fibrillation.

The smartphone ECG showed a good reliability in the analysis of the QRS complex, in assessing both duration and polarity. In most dogs, QRS complexes displayed the same polarity on smartphone tracings and lead II of the 6-lead ECG, with a similar polarity in all cases of ventricular ectopic beats. In comparison to the standard ECG however, the smartphone device underestimated the R wave amplitude. In many dogs it was necessary to use the highest calibration setting (20 mm/mV) to optimally visualize the electrocardiographic waves. Therefore, smartphone tracings should not be used to assess the amplitude of ECG waves as a substitute for standard electrocardiograms.

The smartphone ECG was highly reliable in the identification of ectopic beats. Ventricular premature complexes, accelerated idioventricular rhythms and ventricular tachycardias were easily identified in all cases with the smartphone ECG. One recent investigation used it as the sole electrocardiographic method in the identification of ventricular premature complexes in the screening of Doberman Pinschers for occult dilated cardiomyopathy.[i] It could thus be useful in screening or monitoring dogs with cardiomyopathies associated with ventricular arrhythmias.

With regard to the reliability of the smartphone ECG for AVBs, a good agreement with the standard ECG was found both in the evaluation of the PQ interval and in the identification of the type of block. One study in humans described a higher percentage of false positives and negatives during the evaluation of AVBs compared to our results.[7] The authors reported motion artifacts (arm movement, muscle tension and tremor) as the main difficulties in AVB evaluation. None of the smartphone ECG tracings recorded motion artifacts that led to misdiagnosing AVBs. Thus, the agreement between devices was perfect, suggesting that the smartphone ECG can be helpful in the interpretation of AVBs in dogs.

Lastly, the reliability of the smartphone device in the assessment of the QT interval and ST segment was evaluated. The smartphone ECG underestimated the QT interval in most instances, leading to false negative results in the diagnosis of the long QT. However, in all dogs with an increased QT (QTc > 260 ms), there was a complete agreement. In one study performed on humans, the smartphone ECG was highly reliable in the analysis of the QT interval.[8] In our group, the morphology of the T wave based on the smartphone ECG was not always similar to that reported with the standard ECG. This finding, along with the frequent biphasic morphology of the T wave, makes the evaluation of the QT interval less accurate in dogs. Misclassifications were also found in the ST segment interpretation. Taken together, these findings suggest that the smartphone ECG may only be partially reliable for QT interval and ST segment evaluation in dogs.

Our investigation has some limitations. First, the study group was large but the number of dogs with arrhythmias was relatively low. A larger number of rhythm disturbances might have revealed a lower reliability of the smartphone ECG. However, most common types of canine arrhythmias were included in our study and in all these cases the smartphone ECG was consistent in diagnosing the arrhythmia. Second, during the recording of the smartphone ECG, all dogs were positioned in right lateral recumbency and it is not known if there would have been similar results if the left side or standing positioning was used instead. Furthermore, we recorded 1 minute with both ECG methods, but only the last 30 s were used for the manual HR assessment. As the App HR provided an estimate of the mean HR based on a 1-minute registration, we cannot rule out that the interpretation of the results was partly biased.

In conclusion, the smartphone ECG can rapidly and simply record a single-lead ECG of good diagnostic quality in dogs. Tracing analysis performed by cardiologists reliably evaluated HR, heart rhythm, AVBs and ectopic beats. The smartphone ECG does not substitute the 6-lead ECG or Holter monitoring but does represent an additional tool in the management of dogs with arrhythmias or in monitoring dogs at risk for heart rhythm disturbances. Further studies are needed to assess the diagnostic value of the smartphone ECG recorded by owners in a home setting.

Footnotes

[a] Kraus MS, Rishniw MR, Gelzer AR, et al. Comparison of the Alivecor® ECG device for the iphone with a reference standard electrocardiogram. ACVIM forum 2013. Seattle (WA), USA.

[b] Elan 1100 ECG system, Cardioline, et medical devices SpA, Milano, Italy.

[c] MAC 800 ECG system, GE Healthcare, Milano, Italy.

[d] AliveCor Veterinary Heart Monitor, AliveCor, Inc., San Francisco, CA, USA.

[e] AliveECG Vet, AliveCor, Inc., San Francisco, CA, USA.

[f] Apple Inc, Cupertino, CA, USA.

[g] GraphPad Prism 5, San Diego, CA, USA.

[h] Stromberg V, Kvart C. iPhone ECG and Hypertrophic Cardiomyopathy (HCM) in Cats. Epsilon Archive for Student Projects. Library of the Swedish University of Agricultural Sciences. Uppsala. 2015. Online link: http://stud.epsilon.slu.se/7583 (last access on 06-02-2016).

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Conflict of Interest

The authors disclose no conflict of interest.

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Tables

Table 1. Agreement (κ) between smartphone ECG and standard 6-lead ECG.

Type of analysis	**κ**	**(95% CI)**	**Agreement**
Manual HR	1		Perfect
App HR	0.91	(0.81-0.99)	Very good
Heart rhythm	0.94	(0.86-1)	Very good
AVBs	1		Perfect
Ectopic beats	1		Perfect
ST interval	0.70	(0.43-0.98)	Good
QTc interval	0.72	(0.49-0.95)	Good
QRS polarity	0.65	(0.34 to 0.97)	Good

CI = confidence interval; Manual HR = HR manually measured on printed ECG tracings; App HR = HR automatically measured by smartphone application; AVBs = atrioventricular blocks; QTc = corrected QT interval.

Table 2. Differences between smartphone ECG and standard ECG in the evaluation of electrocardiographic parameters.

Parameter	Difference	Range
Manual HR (bpm)	0	-10; +20
App HR (bpm)	-3	-31; +20
P (ms)	0	-20; +0
P (mV)	-0,1	-0,4; +0,1
PQ (ms)	0	-20; +20
QRS (ms)	0	-20; +10
R (mV)	-0,5	-2,1; +1
QTc (ms)	-10	-34; +19

Manual HR = HR manually measured on printed ECG tracings; App HR = HR automatically measured by smartphone application. Median difference and range are reported.

Table 3. Agreement between smartphone ECG and standard 6-lead ECG in heart rhythm identification in 162 dogs.

	Smartphone ECG				
Standard ECG	**S**	**AF**	**SV**	**V**	**Total**
S	138	2	1	0	141
AF	0	12	0	0	12
SV	0	0	2	0	2
V	0	0	0	7	7
Total	138	14	3	7	162

S, sinus rhythm; AF, atrial fibrillation; SV, supraventricular rhythm; V, ventricular rhythm.

Figure legends

Figure 1. Cranio-caudal orientation of the smartphone in a dog. The camera side of the smartphone was located caudally.

Figure 2. Sinus rhythm with standard ECG (A) and with smartphone ECG (B) in the same dog. Paper speed = 50 mm/s; 10 mm = 1 mV.

Figure 3. Atrial fibrillation with standard ECG (A) and with smartphone ECG (B) in the same dog. Paper speed = 50 mm/s; 10 mm = 1 mV.

Figure 4. Third-degree AVB with standard ECG (A) and with smartphone ECG (B) in the same dog. Paper speed = 50 mm/s; 5 mm = 1 mV.

Figure 5. Pearson test showing a strong positive correlation between the HR values manually measured on standard ECGs and smartphone ECG tracings ($r^2 = 0.99$; $p < 0.0001$).

Figure 6. Bland-Altman plot showing differences between HR values manually measured on standard ECG and smartphone ECG tracings.

Figure 7. Pearson test showing a strong positive correlation between the HR values manually measured on standard ECGs and HR values produced by the smartphone application ($r^2 = 0.92$; $p < 0.0001$).

Figure 8. Bland-Altman plot showing diffences between the HR values manually measured on standard ECGs and HR values produced by the smartphone application.